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A method of improving the analysis of cloud top height for the New Mesoscale Model

by

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A method of improving the automatic analysis of cloud top height for the new mesoscale model

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Abstract

A procedure for determining layer cloud top height in anticyclonic regions has been developed and tested on a number of cases. The method uses METEOSAT infra-red and Mesoscale Model temperature and humidity data. It is anticipated that the method will subsequently be incorporated into an automated version of the Moisture Observation Pre-processing System for the Mesoscale Model.

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1 Introduction

In the New Mesoscale Model (NMM) the analysis of cloud top height forms part of a set of moisture analyses carried out within the Moisture Observation Pre-processing System (MOPS) (Wright 1993). The purpose of MOPS is to provide a three dimensional cloud analysis as profiles of relative humidity. These data can then be assimilated into the NMM in much the same way as radiosonde ascents. Currently the MOPS analysis is a menu-driven system operated by a forecaster on an interactive graphics workstation. The forecaster monitors the use of surface observations and satellite and radar imagery in the production of analyses of precipitation rate and type, total cloud cover, cloud base and cloud top height (CTH). These analyses are then used, with additional information from surface cloud reports, to modify the model first-guess (FG) fields to generate the three dimensional cloud analysis. After the analysis, the forecaster has the opportunity to check and modify the vertical cloud structure. The reason for this is to minimise the introduction of gross errors in the total cloud cover and CTH fields. It is planned to automate the MOPS during 1993. Before this can be achieved, satisfactory methods of diagnosing cloud cover and CTH need to be developed. At present the assignment of CTH is made by matching the brightness temperature of the METEOSAT infrared (IR) image with a model temperature by scanning upwards through the levels. Cloud top is usually associated with a temperature inversion, which can be very pronounced for persistent stratocumulus sheets. These inversions are often not well-resolved by the model. This means that the matched temperature will not correspond to the cloud top but to some point much higher where the cloud-free environment temperature has fallen to the observed satellite IR value. This problem can lead to height assignment errors of several thousand feet for stratocumulus clouds. The method described in this paper addresses this problem by proposing an alternative approach to determining cloud top height.

2 The method

This method takes as its starting point an idealized vertical temperature and humidity profile through a stratocumulus cloud layer (figure 1). The main features of this structure will now be summarised. A more detailed description can be found in Bennetts et al (1986). In the region above the cloud the air is warm and dry through subsidence. At the cloud top there is a marked inversion and hydrolapse. The cloud top temperature is that at the base of the inversion. The boundary between the cloud layer and the subsiding air is generally a few tens of metres. Within the cloud the air is well mixed (turbulent) and has a constant wet-bulb potential temperature (WBPT). At the base of the cloud layer the transition to clear air is poorly defined. In contrast to cloud top, the cloud base region has no strong temperature gradients and stability to vertical motion is weak. In consequence cloud base is diffuse and large perturbations can grow as is evident from the rolls that are frequently observed in stratocumulus sheets. Beneath the cloud the air is also well mixed with the WBPT the same as in the cloudy layer. However, relative humidity decreases downwards. The temperature lapse usually approximates the dry adiabatic value and the humidity mixing ratio is constant. Close to the surface either a super-adiabatic lapse or an inversion may occur because of non-adiabatic processes, for example, radiation.

The use of this idealized profile in the new scheme for determining CTH is illustrated in figure 2. In the scheme a model temperature and dewpoint for a level near the surface are selected. Starting from the reference level temperature value the air is cooled adiabatically until it becomes saturated. This occurs at the condensation level (Normand's point) and is taken to be the cloud base. From this point the air is cooled at the saturated adiabatic lapse rate until the satellite IR temperature (Tsat), which is assumed to be the cloud top temperature, is reached. If the derived temperature at cloud base is lower than Tsat then the cloud top temperature is set to the cloud base temperature. Using the temperatures and dewpoints at the cloud top, cloud base and reference level, a layer thickness is calculated using the hydrostatic equation. The height of the model reference level above ground is then added to the thickness to obtain cloud top height.

This scheme is obviously sensitive to errors in the model reference temperature and dewpoint and the cloud top temperature. Given a correct profile above the reference level, an error of 1 deg C in cloud top temperature will, within the usual ranges of cloud top temperatures and height, give rise to an error of around 500 feet in CTH. The effects of errors in the reference temperature and dewpoint values depend on how they affect the wet-bulb potential temperature. Provided that the cloud base temperature is greater than Tsat then a decrease in WBPT will lead to a cooling in the derived temperature of the cloudy layer and a lower CTH. Conversely, an increase will give a higher CTH. If the derived cloud base temperature is lower than Tsat then the CTH will again be too high. Therefore, provided the model WBPT is sufficiently good, the accuracy of the CTH will depend on the suitability of the scheme for a particular occasion and the error in the cloud top temperature. In many cases these criteria are related. Large errors in the cloud top temperature of a stratocumulus layer are likely to be caused either by an incomplete coverage of the field of view (FOV) of the satellite pixel or contamination from higher cloud. Errors arising from absorption by water vapour are assumed to be negligible in the very dry conditions above a layer of anticyclonic SC cloud. However, they may be significant in other scenarios. In the case of persistent anticyclonic stratocumulus cloud, contamination by higher cloud is generally negligible because of the subsidence aloft. Also the cloud sheets are usually uniform with smooth tops, completely covering the FOV for many kilometres, though there will be difficulties at the edge of the cloud sheets. Therefore, in these synoptic types the scheme should perform well given a reasonable WBPT. It is possible that the scheme could also be applicable to other situations. In cases of multiple cloud layers extending high into the troposphere where the WBPT is representative through the layers, the CTH should be a good estimate for the top layer.

3 Application of scheme

A method has been devised of determining where the scheme may be applicable using surface synoptic reports and METEOSAT IR data.

- Surface land and ship synoptic reports over the model area are examined. Those reports containing observations of greater than or equal to 7/8 stratus (ST) or stratocumulus (SC) cloud (cloudy) or less than or equal to 5/8 total cloud cover (clear) are extracted. The reports of clear conditions are important as they are used to determine regions where the satellite IR temperature is unlikely to be representative

of the cloud top temperature.

- For each of these reports the model gridsquare containing the observation position is identified. If the gridsquare contains a cloudy report then the gridpoint value is set to 0. If the report is clear it is set to 1. All remaining gridpoints are set to a value corresponding to a missing data indicator (MDI).
- The procedure now loops round each gridpoint working from the bottom left hand corner to the top right hand corner (SW to NE) of the grid. If a gridpoint has a value not equal to MDI then its neighbouring points are set to its value (0 or 1) provided they are equal to MDI. The loop is then repeated 4 times. The effect of this is to duplicate zeroes and ones round each gridpoint within a radius of 5 model grid lengths.

The outcome of this procedure over the land areas of the model, because of the relatively high density of cloud observations, would be to classify each gridsquare as containing either greater than 6/8 ST or SC cloud, value 0, or clear (less than 6/8 total cloud), value 1, or greater than 5/8 total cloud cover comprising mainly cumuliform, medium or high cloud, value MDI. It is also possible that a few gridpoints over land will be set to MDI because no nearby cloud observation was available. The order of looping round the gridpoints is arbitrary. In the order specified here gridpoints to the south and west would be 'expanded' before those to the north and east. The effect of this is to duplicate any vacant gridsquare within the range of 4 gridpoints with the value of the southwesternmost gridpoint. Looping round the grid in different orders, for example NE to SW would change the designation of a few squares where gridpoints meet. Experiments with different looping orders indicate that differences in classification are very small and do not exceed 1 gridsquare.

Over the open sea most gridpoints will be unclassified because of the lack of surface cloud reports. To define the cloudy regions METEOSAT IR temperature (Tsat) and model surface temperature (Tstar) data are used. The first step is to interpolate the Tsat values onto the model grid. These gridpoint values of IR temperature are then compared with Tstar over the sea. A gridpoint is said to be cloudy if Tstar - Tsat is greater than 10 deg C. This is the same threshold used in MOPS to determine which METEOSAT IR pixels are cloudy. All cloudy points are set to 0.

The CTH scheme is applied to all gridpoints with a value equal to zero. The cloud top temperature used in the scheme is the interpolated Tsat value.

4 Case studies

In order to test the CTH scheme 4 casestudy dates were chosen; 4/12/91, 27/12/92, 30/12/92, and 8/3/93. On each of these days anticyclonic conditions with stratocumulus sheets occured over large areas of the NMM domain. On two of the days, 30/12/92 0000 GMT and 08/03/93 0600 GMT, there was a front to the west of the British Isles. In order to make the best use of existing software the METEOSAT IR data were extracted from the FRONTIERS archive. The FRONTIERS area is slightly less than the NMM (Brown et al, 1993). The NMM data were interpolated from the equatorial grid of the model onto a pseudo National Grid projection with 89 x 91 gridpoints over a domain

closely approximating the Old Mesoscale Model (OMM) (Pre 8/12/92) (Sinclair, 1993). Synoptic surface reports were extracted from the Synoptic Data Bank using standard routines.

4.1 Determining regions to apply scheme

The results of the procedure for determining the regions over which to apply the CTH scheme are shown in figure 3. The applicable regions are shaded in red and green. The red areas were obtained from the surface reports and the green from IR data and model Tstar. The edges of the FRONTIERS region can be seen clearly in the diagram for 4/12/91. This picture gives a good representation of the stratocumulus distribution at 0000 GMT. The clear tongue extending NW and SE from Brest is somewhat artificial and comes as a result of the algorithm for extending the influence of each report. 3/8 SC was observed at Brest whereas a ship to the NE and a nearby station to the south both reported 8/8 ST. On 27/12/92 at 0000 GMT a hole in the SC sheet to the north of Southampton was analysed. Southampton Weather Centre reported 5/8 SC whereas at St Catherines Point, on the southern tip of the Isle of Wight, 8/8 cover was observed. This means that the clear area is only extended northwards from Southampton rather than southwards as well. The clear region around RAF Valley in Anglesey which reported clear skies is also prominent. At 0000 GMT on 30/12/92 the SC and ST cover was patchy and this is indicated in the diagram. On 8/3/93 at 0600 GMT the edge of the 7/8 SC/ST sheet over SE England extending southwestwards to the Channel Islands was extremely well delineated and agreed with the manual analysis of cloud. The holes over Eire and NE Scotland were also realistic.

METEOSAT IR and model Tstar images for each of the casestudy dates are shown in figure 4. Radiosondes indicated that SC cloud top temperatures were in the range 0 to -10C on each day. This suggested that a slicing interval of 10C for the images would be convenient. In the IR image for 8/3/93 the edge of the SC sheet over SE England is well marked, extending down to the Channel Islands. The frontal system in the west shows up as a region of lower cloud top temperature. Most regions coloured blue over the sea are designated clear in the final analysis (figure 3), the exception being where the analysis of synoptic reports indicates otherwise, for example, over the Irish Sea and in the North Sea. In the 30/12/92 case the Tstar field shows very low temperatures over eastern England and Scotland where freezing fog was observed at many sites. The imagery suggests most of the area to the west of the UK is cloudy, however, there are a few holes in the Bristol Channel, the southern Irish Sea and near the west coast of Scotland. These are also indicated in the synoptic report analysis (figure 3) and confirms the value of surface cloud observations. On 27/12/92 possible clear regions near Anglesey and to the north of Southampton are indicated. The ribbon of blue extending east from the Isle of Wight along the English Channel through the Dover Straits and into the southern North Sea is also possibly clear. This agrees with two ship reports giving clear conditions shown in figure 3. On 4/12/91 the lines of cold cloud extending eastwards into the North Sea are cirrus and altocumulus with stratocumulus beneath closer to Norway. This is depicted by the ship reports in the analysis shown in figure 3. The benefit of these reports is evident in the clear region just to the east of Scotland which would have been designated cloudy using only the satellite analysis.

4.2 Sensitivity and verification

In order to test the sensitivity of the CTH scheme to the choice of model reference level, five sets of cloud top heights were derived each starting from a different level. In the NMM cases the bottom 5 levels were used which are nominally 25, 90, 180, 300, and 440 metres above ground. For the OMM case (4/12/91) levels 1,5,7,8, and 9, which are exactly 1.25, 20, 70, 115, and 175 metres above ground, were used. Figure 5 shows the CTH fields obtained by using FG temperature and dewpoints at 0000 GMT on 27/12/92 for levels 1, 3 and 5. It is immediately apparent that differences are small over sea areas but large over land. Over the land, CTH increases with increasing reference level height. The reason for this is that the model FG WBPT decreases near to the ground, presumably because of radiative cooling. This is evident in the negative Tstar values over most of the land shown in figure 4. It is over these regions that CTH varies the most. Figure 6 shows two tephigrams from the NMM FG fields for 0000 GMT 27/12/92 labelled A and B. The locations of the soundings are shown in figure 5 near the bottom right and top left corners of the grid respectively. Tephigram A, which is in a region where CTH varies considerably, shows a steep temperature inversion and an increase in WBPT with height in the lowest 100 millibars. Conversely, tephigram B has an almost constant WBPT. This comparison shows that in regions where model WBPT changes markedly with height, CTH will be very sensitive to choice of reference level.

In order to decide on the the reference level that gives the best CTH on most occasions, the derived heights were compared with diagnosed heights from radiosondes where available. CTH was diagnosed from the radiosonde data by examining the temperature minus dewpoint differences (T-Td) from the top of the sounding downwards. The first level where T-Td was less than or equal to 1.5 deg C was taken as the cloud top height. The choice of 1.5 deg C for the dewpoint depression was a compromise between values quoted in Layer Cloud Forecasting notes (1992) for 8/8 cloud cover, which are temperature related. The quoted ranges are that if the dry bulb is >= 0 deg C then T-Td should be less than or equal to 1 deg C, otherwise less than or equal to 3 deg C. In the cases examined here a depression of 1.5 deg C, apart from one sounding on 27/12/92 (see later), gave cloud top heights at the inversion level and proved to be a reliable indicator of solid cloud layers. However, it was noticed that on a few occasions cloud was erroneously diagnosed close to the ground, because of mist or fog. Therefore, any cloud top heights diagnosed below 100 feet were set to zero. CTHs from each available radiosonde for the casestudy dates are plotted in figure 7. These plots are useful in that there is enough information to detect trends in the height fields. On 4/12/91 CTH increased from SE to NW with values just above 3000 feet over much of England and Wales. This SE to NW trend is repeated on 27/12/92 but with steeper gradients. Over the near continent the cloud is ST below freezing, whereas over the UK it is ST and SC, thick enough in places to give rain and drizzle. On 30/12/92 the cloud is more variable but an east-west difference is evident. On 8/3/93 only UK sonde data were available at 0600 GMT and these again showed an increase in CTH from SE to NW.

Cloud top heights were calculated using the test scheme from two sources of model data. One set used FG fields and the other used analysed fields at T+0 (INIT). Operationally any new scheme would be expected to work with FG fields; however, using the T+0 fields provides a useful benchmark since the INIT temperatures had the benefit of radiosondes and surface reports in the analysis and should, therefore, be better than the

FG temperatures. MOPS would also have been carried out. Each set of CTH fields were compared with the radiosondes provided both the CTH for the gridsquare at the sonde location and the sonde CTH were non-zero. The NMM case results were combined and root mean square errors (RMSE) and mean errors for the test scheme minus sonde were calculated. The statistics are shown in figure 8. The number of occasions when a comparison could be made for each set was 24 and the sonde cloud heights were distributed approximately normally with most of the heights in the range 2000-4000 feet. RMSEs obtained using the FG were higher than those from the INIT for each reference level. The lowest RMSE was about 1000 feet in both the FG and INIT for level 2. The RMSE doubles going from level 3 to level 5. The mean errors are interesting and show that using the FG the sign of the error changes from negative below level 3 to positive above. This indicates an increase in WBPT with height. The rate of increase is halved in the INIT results. The effect of the analysis is to lower the WBPT of the model FG, particularly above level 2. The optimum reference level chosen from the FG was level 3 (180m) which had an RMSE of 1048 feet and a mean error of 31 feet. Similar statistics were produced for the 4/12/91 case using 11 comparisons. Root mean square errors from the FG and INIT were similar with the INIT lower. The lowest from the FG was 1390 feet for level 8 (115m). The corresponding mean error was -164 feet. In the NMM cases the MOPS cloud cover fields were also compared with the sonde reports. To determine a CTH field from the MOPS output a threshold of 5/8 cover was used, above which a gridpoint was set to cloudy. At the model column corresponding to each radiosonde site, cloud fraction was scanned from top to bottom and the first level where it exceeded 5/8 was taken as the CTH. The comparisons produced a RMSE of 3071 feet and a mean error of 1461 feet. In terms of RMS these results are a factor of 3 poorer than the test scheme. MOPS produces a greater variability of CTH than the new scheme. This is self-evident in the CTH charts which will now be discussed.

4.3 Height fields

Derived CTH fields from the test scheme and MOPS are shown in figures 9 to 11 for the 27/12/92, 30/12/92, and 8/3/93 cases respectively. In each of these figures level 3 (180m) is the reference level used to determine the CTH with the new scheme from the FG and INIT. In the following discussion the sonde heights plotted in figure 7 will be compared with the height fields. In the 27/12/92 case the CTH fields from the new scheme reflect the gradual increase in CTH from SE to NW. There are only small differences between the FG and INIT. The most significant difference is in the region of the low cloud over NE France and Holland. Observed heights are around 1000 feet and these are analysed better from the INIT than the FG. Other parts of the region all verify well from the FG. The height fields produced by the new scheme are smooth and, given the stable nature of SC cloud, realistic. The MOPS output shows CTH to be much higher than the test scheme over most of the UK. This was unrealistic as can be seen in the tephigrams for Hemsby shown in figure 12. The observed sounding is shown on the left and exhibits the textbook structure through a layer of SC cloud. The observer on the ground reported 8/8 cover at 2700 feet. The method for estimating CTH from sondes gave 2666 feet. Assuming the observed base is accurate, the discrepancy may be explained by the fact that T-Td is only less than or equal to 1.5 deg C (the criterion for cloud) at the cloud base. The cloud top, or the base of the temperature inversion, is 20 mb above this. For this sounding, the

true CTH is likely to be around 3300 feet with a cloud top temperature of -1 deg C. The observed cloud top temperature matches that from METEOSAT exactly. The sounding from the INIT for a gridpoint close to Hemsby has the inversion too low and a spurious moist layer between 750 and 800 millibars. This spurious layer has been inserted by the automatic MOPS procedure for matching the FG profile to the IR temperature. This incorrect height assignment is typical of other regions of the UK in this case. Over the ocean to the NW of the UK the high cloud analysed by MOPS broadly agrees with that from the test scheme.

The results for 30/12/92 shown in figure 10 are the worst of all the cases for the test scheme. All of the outputs show the frontal system in the NW of the region as an area of increasing CTH. Over the mainland UK the observed cloud was patchy ST and SC. Over England and Wales the stratus was very low and thin in many areas. Sonde cloud top heights are below 1000 feet over Northern England (figure 7) . The Leeming radiosonde shown in figure 13, which gave a CTH of 781 feet, was typical of the conditions in this area. The low stratus, which had a base around 100 feet, is indicated by the near saturated plot near the surface. The observed cloud top temperature was -4 deg C which again agreed precisely with the METEOSAT IR temperature. MOPS produced a good CTH analysis in this region. The test scheme from the FG gave bases which were much too high. The reason for this can be seen in the model ascent for Leeming. The model is too warm and dry in the lowest 50 millibars. At 1000 millibars, for example, the FG WBPT is 1.5 deg C warmer than observed. Applying the test scheme to this ascent from level 3 (approximately 990 mbs) gives a cloud base around 875 mbs at a temperature of -8 deg C. Since Tsat is > -8 the CTH is set to the cloud base at 875 mbs which is 110 mbs higher up than that observed. A possible solution to this problem would be to follow a saturated adiabat upwards from the wet-bulb temperature of the reference level until Tsat is reached. In this example this would provide a CTH of 945 mbs, still too high but closer to the observed height. The CTH obtained from the INIT was closer to the truth but again too high. This problem with the new scheme will occur with warm cloud top temperatures and a FG boundary layer that is too dry. These conditions will probably often occur with low thin stratus. In the areas where CTH is observed to be above 1000 feet the test scheme performs satisfactorily and comparable to MOPS. However, at Cardiff and Stornoway MOPS gives heights which are too high.

In the 8/3/93 case the increase in CTH from SE to NW is very well analysed by the test scheme from the FG. All heights compare well with the sonde values. Particularly well portrayed is the sharp increase in CTH over west Wales and the Lancashire coast. The frontal system further west stands out well as a region of high cloud tops. The analysis from the INIT is similar but not quite as good with cloud heights being slightly lower. The fields from MOPS appear more ragged and do not show the gradient of cloud top height evident in the radiosondes. The effect of human intervention is also obvious in the rather unrealistic rectangular region of higher CTH over SW England. The significant cloud cover has also been extended too far east over SE England and the Channel Islands. Manston on the east coast of Kent reported 1/8 cirrus total cloud and Jersey 1/8 low stratus. Gaps are also evident in the cloud cover over Wales and Northern England where no cloud observations are available. The test scheme fills these areas with cloud. The cold IR temperatures from METEOSAT suggests that this was correct. The region of high cloud top above 11000 feet over Eire in the MOPS output also looks peculiar and is

almost certainly spurious. In comparing the test scheme CTH output with the IR image shown in figure 4 it can be seen that there is a good correspondence. The extra detail and structure in the CTH field provided by the variability of the reference level temperatures blends in well. This is in contrast to the MOPS CTH field which does not correlate as closely.

The 4/12/91 case from the OMM clearly illustrates the effect of human intervention in producing the INIT (figure 14). Large regions of uniform CTH have been interactively analysed. This is unrealistic, and in places still incorrect. For example, at Valentia and Crawley analysed heights are too high. The outputs from the test scheme show much more structure and verify closely with the radiosondes. The increase in CTH going northwestwards is very well modelled. The only poor area is around Holland and Belgium and parts of northern France where the analysed heights are too low. The reason for this was that the model WBPTs were too cold in a region of low stratus with observed screen temperatures around -2 deg C. Apart from the region over the near continent this case was a classic one of anticyclonic SC, so it is perhaps not too surprising that the test scheme performed very well. However, the detail in the CTH fields and the close correspondence with the imagery are very encouraging.

5 Conclusions and Recommendations

The main conclusions that can be drawn from this study are summarised as follows.

- Given anticyclonic stratocumulus conditions the test scheme is capable of producing cloud top heights which are generally as good as and quite often better than the interactive MOPS. The height fields can be expected to be smooth and to exhibit realistic detail in broad agreement with the satellite temperature data.
- The test scheme is sensitive to the choice of model reference level and the accuracy of the WBPT. NMM level 3 appears to be the optimum level to use.
- Problems are likely to arise when the satellite temperature is higher than the derived cloud base temperature. Possible solutions are to either use a lower reference level or to construct a SALR from the reference wet-bulb temperature.
- The procedure to determine where to apply the test scheme accurately defines the regions of significant ST or SC cloud over the land, and areas of cold cloud over the sea. Artefacts may be introduced as a result of the area expansion algorithm combined with the distribution of cloud observations.
- The new scheme produces sensible cloud top heights in regions where thick multiple cloud layers are present as opposed to just low stratiform cloud.

Given these conclusions it is recommended that the CTH scheme outlined in this paper could be incorporated into an automated MOPS. However, some care is required. The method of defining where the scheme is applicable would only pick out stratiform cloud regions over the land. It may be possible to apply the scheme in other regimes, for example convective, provided we are confident that the satellite temperature approximates the cloud top temperature. In order to do this the new scheme could be applied wherever MOPS analyses cloud. In the cases where the satellite temperature is warmer than the

cloud base temperature, the MOPS CTH could be used as before and merged with surrounding heights from the new scheme. It is likely that this will only be a problem over land. Since it would not be appropriate to analyse cirrus heights using the new scheme, it could be restricted to those regions where satellite cloud top temperatures are greater than -20 deg C. In the ICAO atmosphere this is at around 18000 feet. The new scheme also produces a cloud base, and this may prove to be useful over the sea where very few cloud observations are routinely available.

6 References

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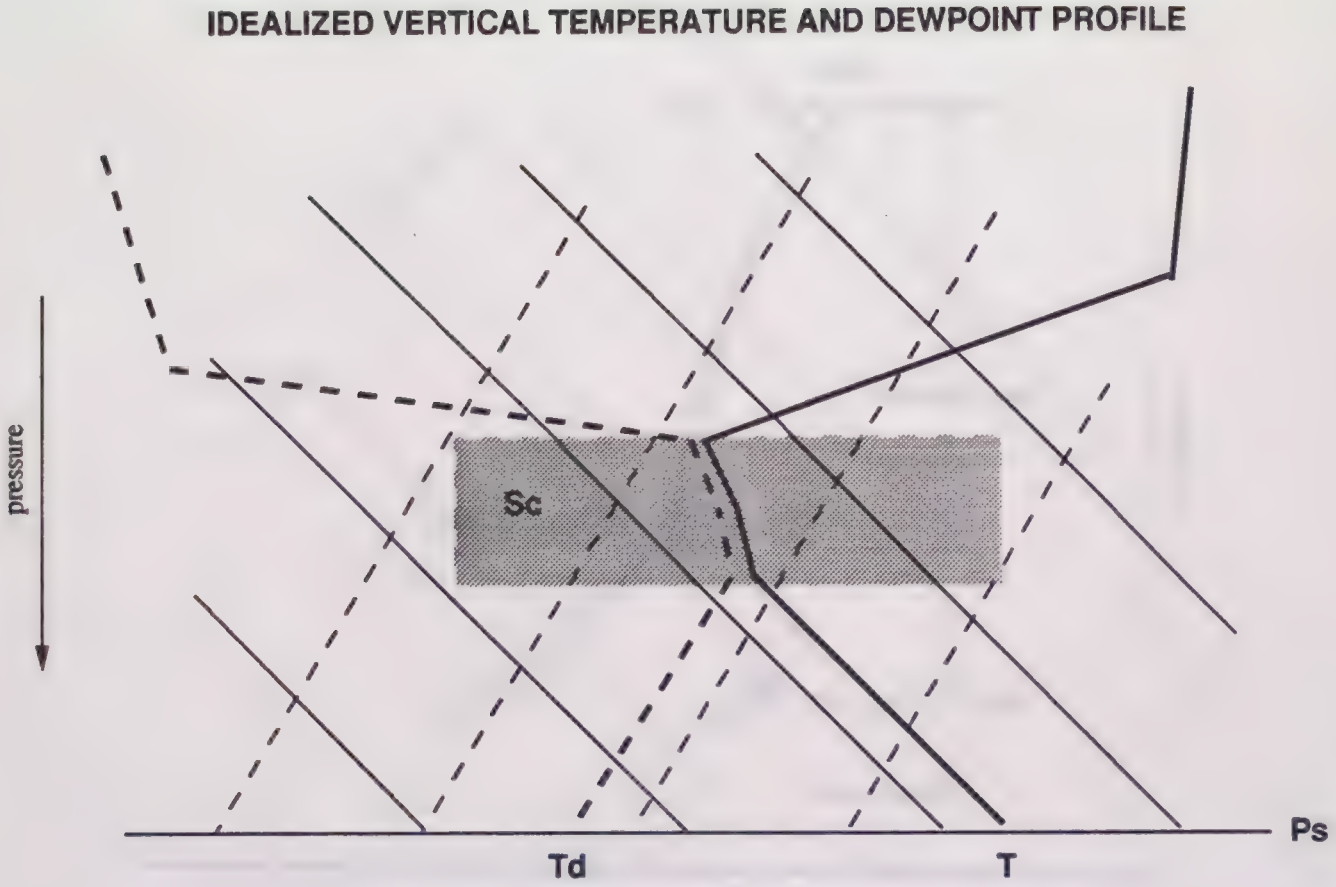

Figure 1.

Idealized tephigram through a layer of stratocumulus cloud. The temperature profile is shown as a solid black line and the dewpoint as a dashed line. The cloudy region is shaded and labelled Sc. Pressure decreases upwards and dry adiabats are indicated by faint solid lines and isopleths of constant humidity mixing ratio by faint dashed lines. Ps is the surface isobar and T and Td are the near surface temperature and dewpoint respectively.

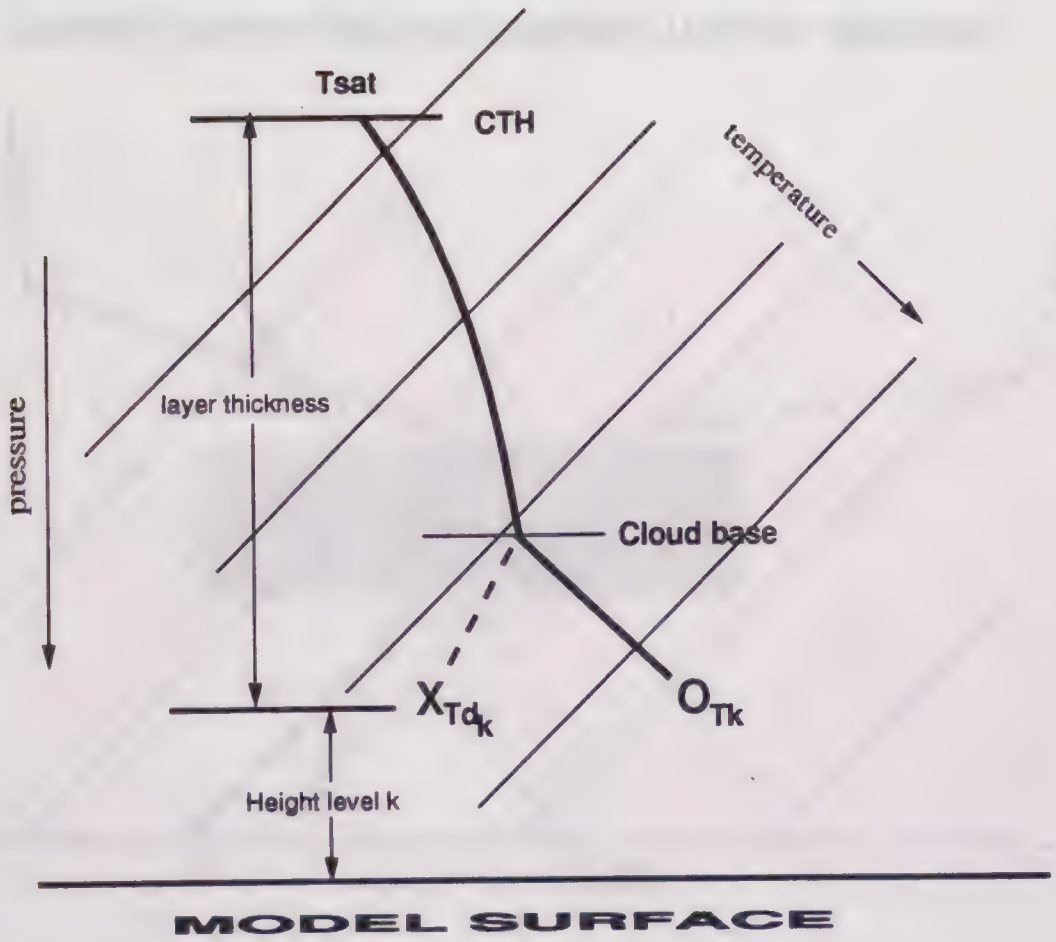

Figure 2.

Simplified tephigram illustrating how cloud top height is derived in the new scheme. "O" is the model temperature at height k above the model surface and "X" is the corresponding dewpoint. Below cloud the thick solid line indicates a dry adiabat and the dashed line constant humidity mixing ratio. Above the cloud base a constant saturated humidity mixing ratio isopleth is followed until the satellite temperature Tsat is reached. The cloud top height (CTH) is then calculated from the layer thickness and the model level height.

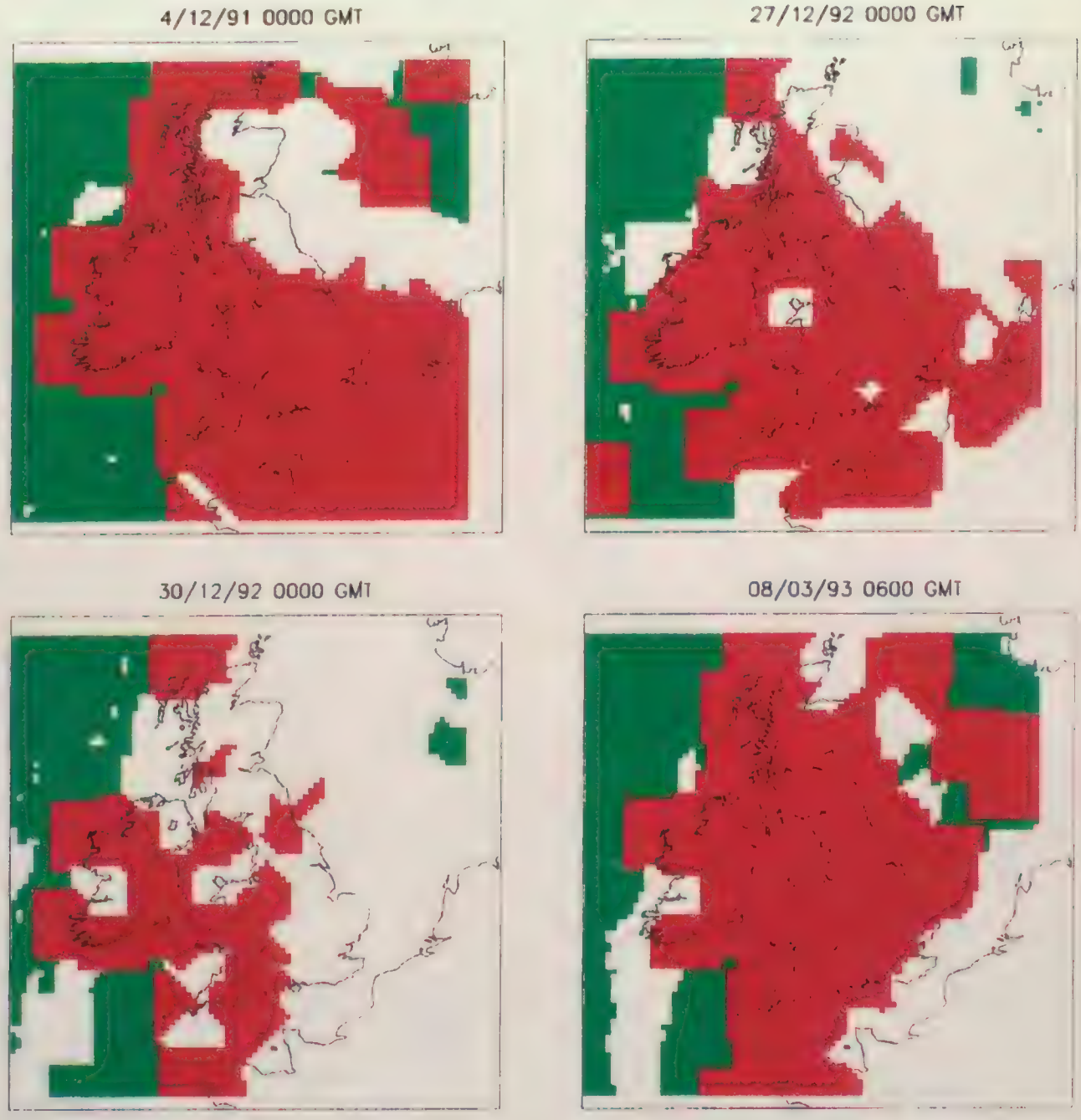

Figure 3.

Coloured regions indicate areas over which the test scheme was applied for each of the casestudy dates. Regions coloured red were obtained from synoptic reports of greater than 6 octas stratus or stratocumulus cloud as explained in the text. The green regions show where cloud was diagnosed over the sea using METEOSAT IR temperature data. Cloud is diagnosed if the satellite temperature is more than 10 deg C lower than the model surface temperature.

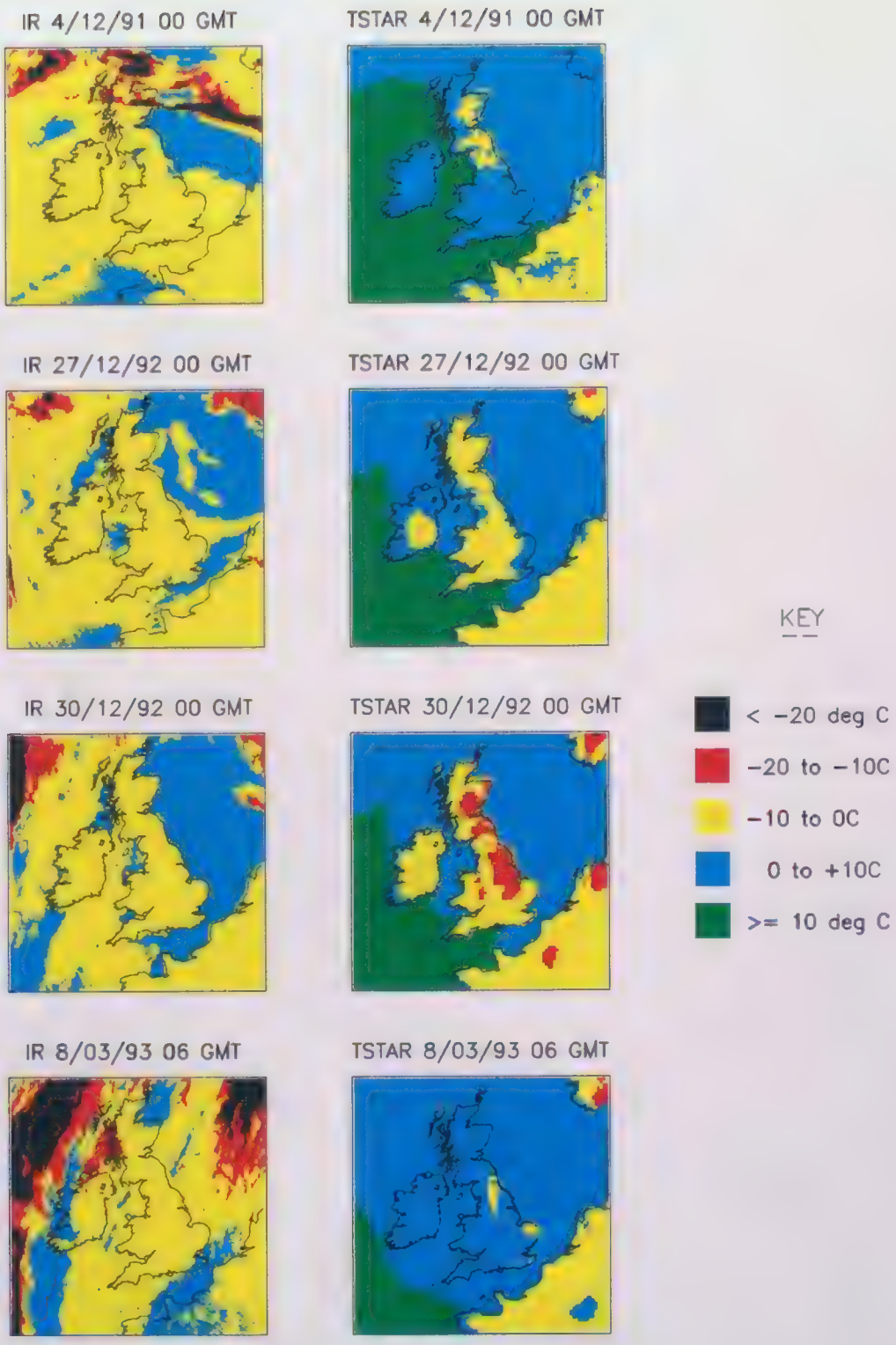

Figure 4.

METEOSAT IR temperatures and mesoscale model surface temperature fields for 4/12/91, 27/12/92, 30/12/92 and 08/03/93 test cases.

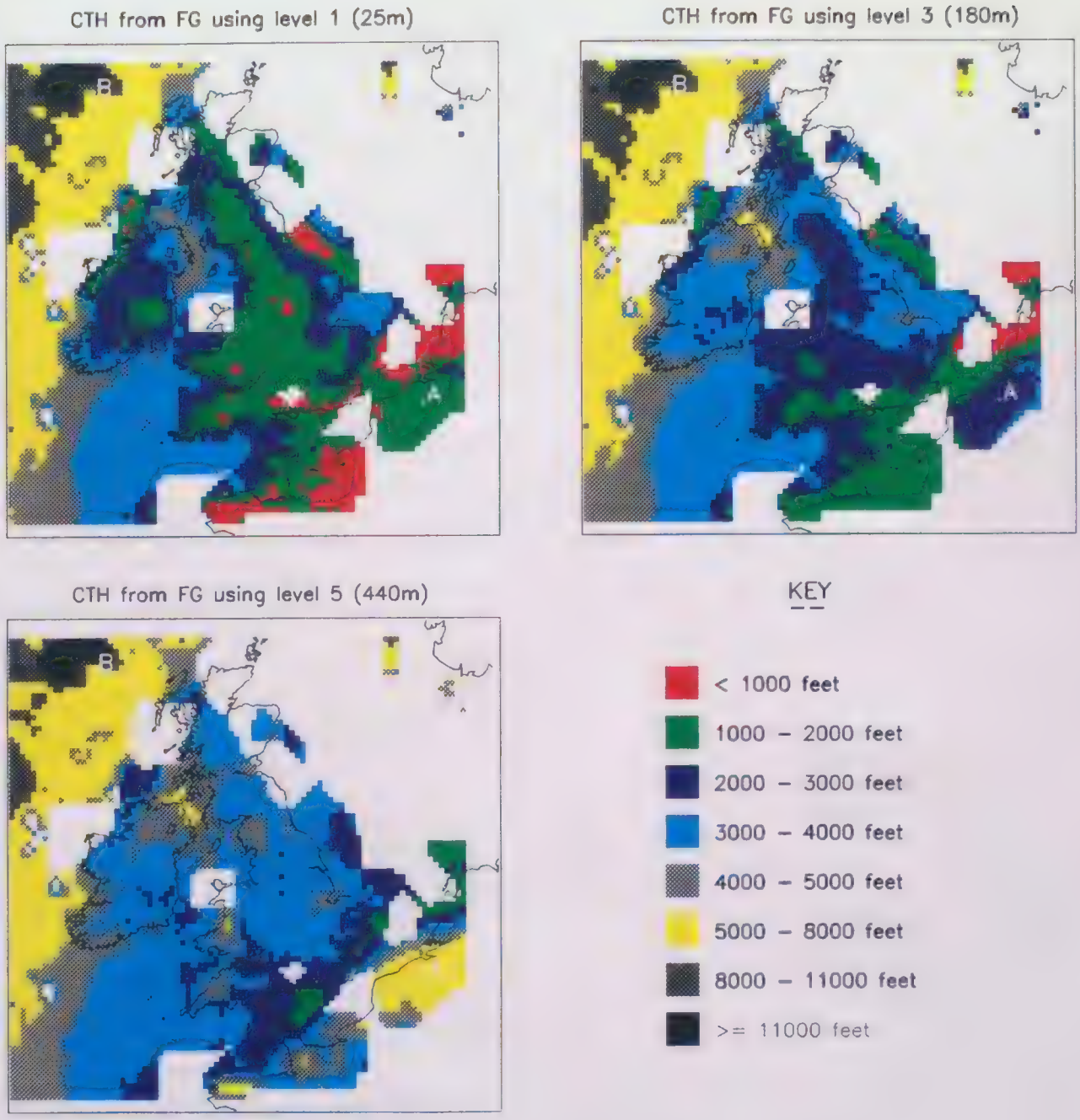

Figure 5.

Cloud top height (CTH) for 0000 GMT 27/12/92 obtained by applying the test scheme from temperature and dewpoint data at each of three model levels for the first guess. The level heights indicated in the captions are nominal. Letters "A" and "B" indicate the location of the tephigrams shown in figure 6.

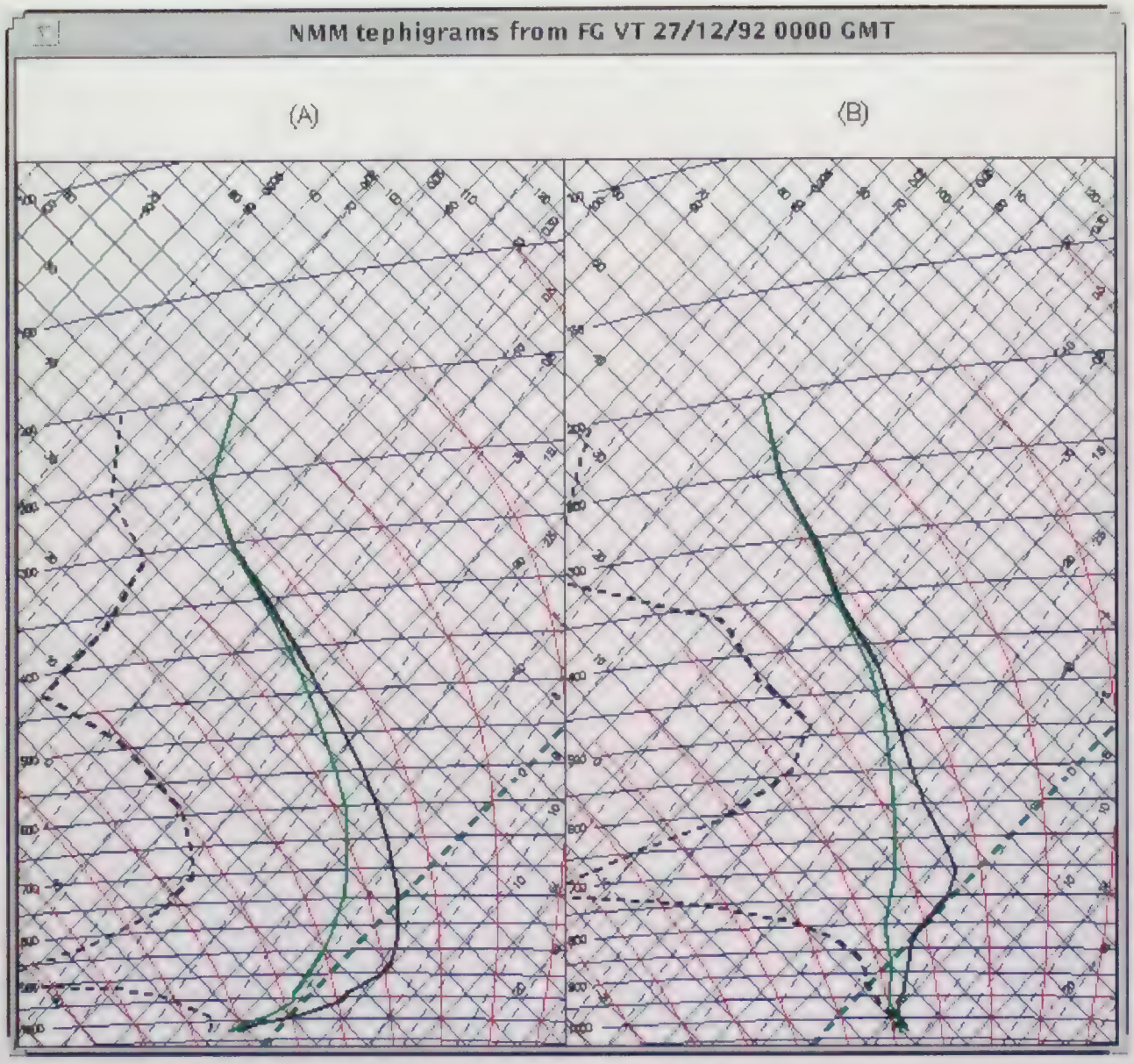

Figure 6.

Tephigrams from the NMM FG for 27/12/92 at 0000 GMT. The locations of the gridpoints are indicated as "A" and "B" in figure 5.
Temperatures are shown as solid black lines, dewpoints as dashed lines and wet–bulb temperature as solid green.

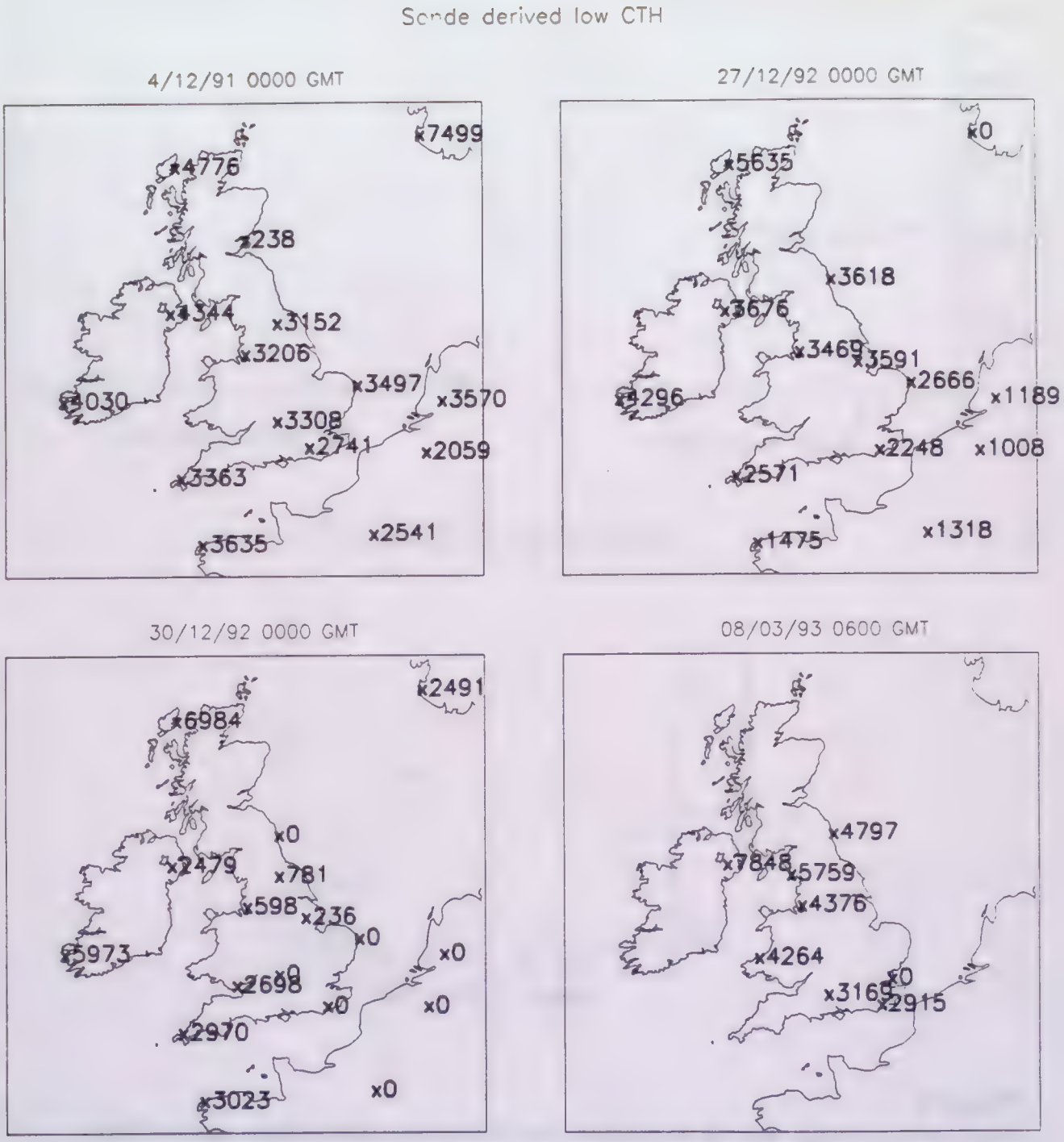

Figure 7.

Cloud top height (CTH) derived from radiosonde soundings.
All heights are in feet above station level and cloud is taken to be present where the difference between temperature and dewpoint is less than or equal to 1.5 deg C. A "x" indicates radiosonde location and 0 means that no cloudy layers were detected.

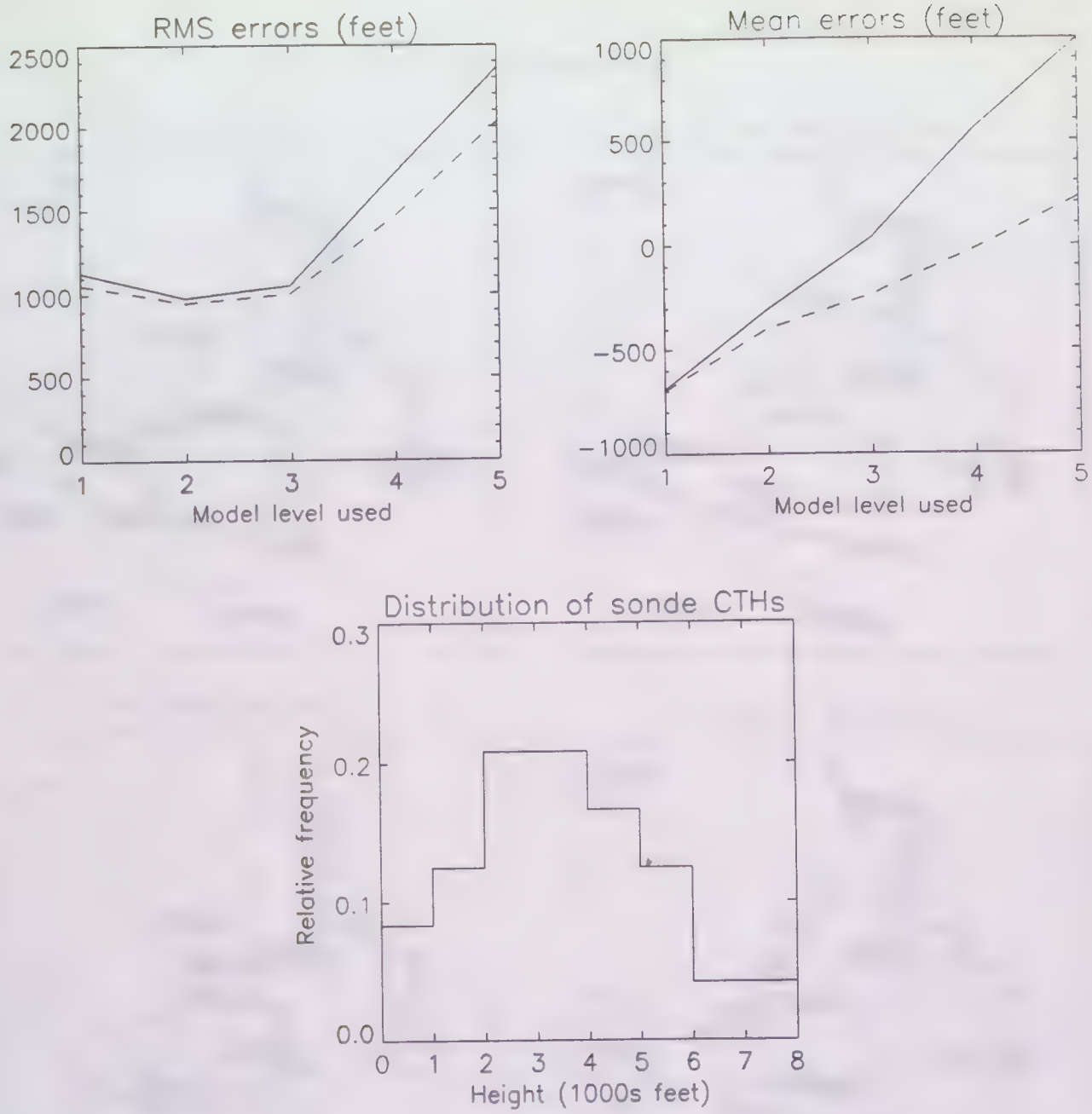

Figure 8.

Plots of root mean square and mean errors for cloud top heights derived from the test scheme starting from different model levels. Results using first guess fields are shown as solid lines and those using T+0 fields as dashed lines. The derived heights were compared with radiosonde cloud heights in the 27/12/92, 30/12/92 and 08/03/93 cases. The distribution of the sonde cloud heights is shown as a histogram below. The number of occasions was 24 and a comparison was only performed if both the test scheme and the radiosonde diagnosed cloud.

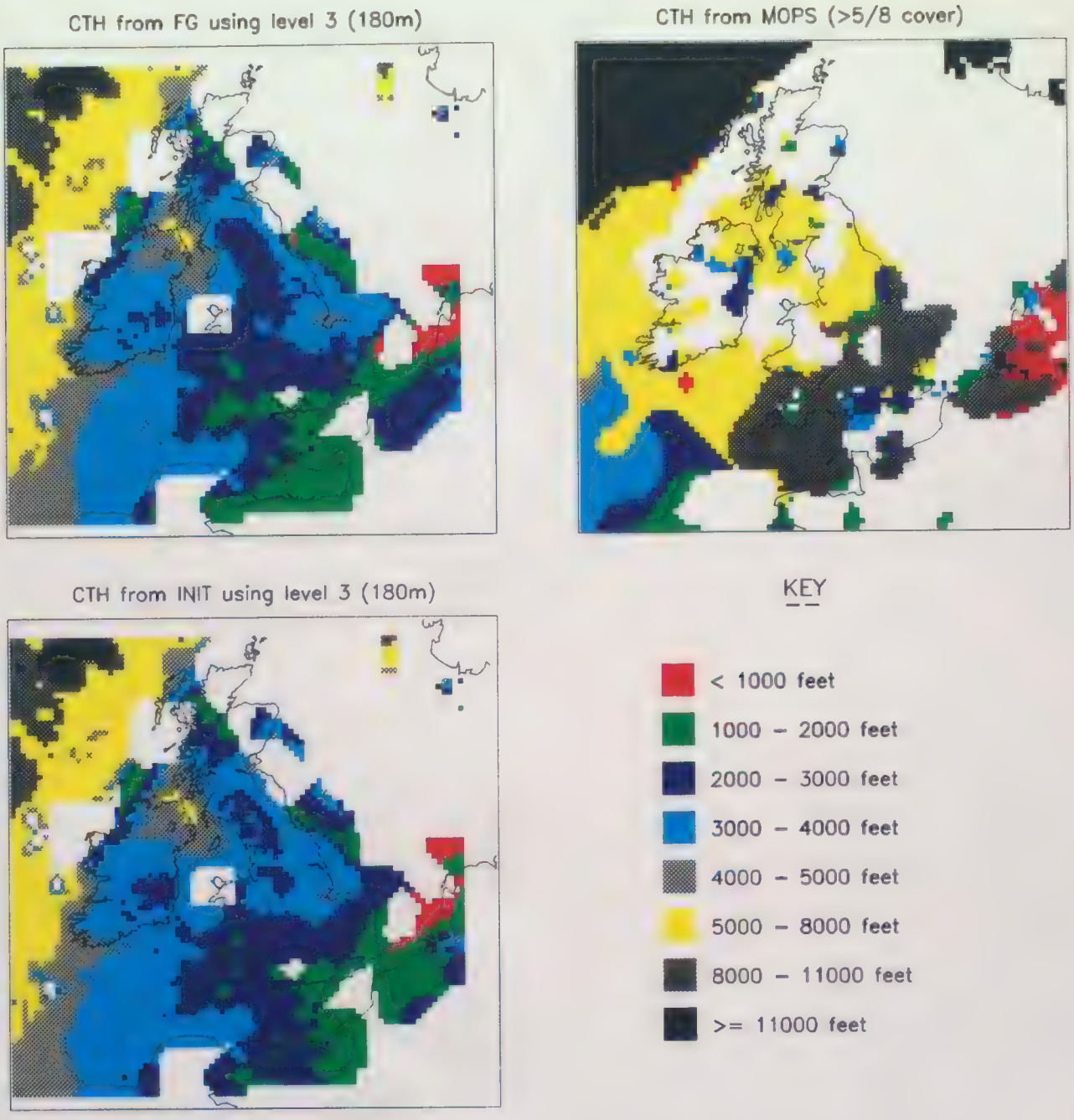

Figure 9.

Cloud top height (CTH) obtained from 3 sources each valid at 0000 GMT 27/12/92. The heights in the leftmost diagrams were derived using the test scheme from temperature and dewpoint data at model level three (approx 180m). In the upper picture a first guess (FG) 3 hour forecast was used to supply the temperature and dewpoint data. In the lower picture a T+0 (INIT) forecast start field was used. The height field in the diagram at the top right was derived from the results of the moisture observation pre–processing system (MOPS) which outputs cloud cover at model gridpoints. The height of the highest layer of cloud is shown provided that it covers more than 5/8 of a grid square. The CTHs in all diagrams are all relative to the model surface.

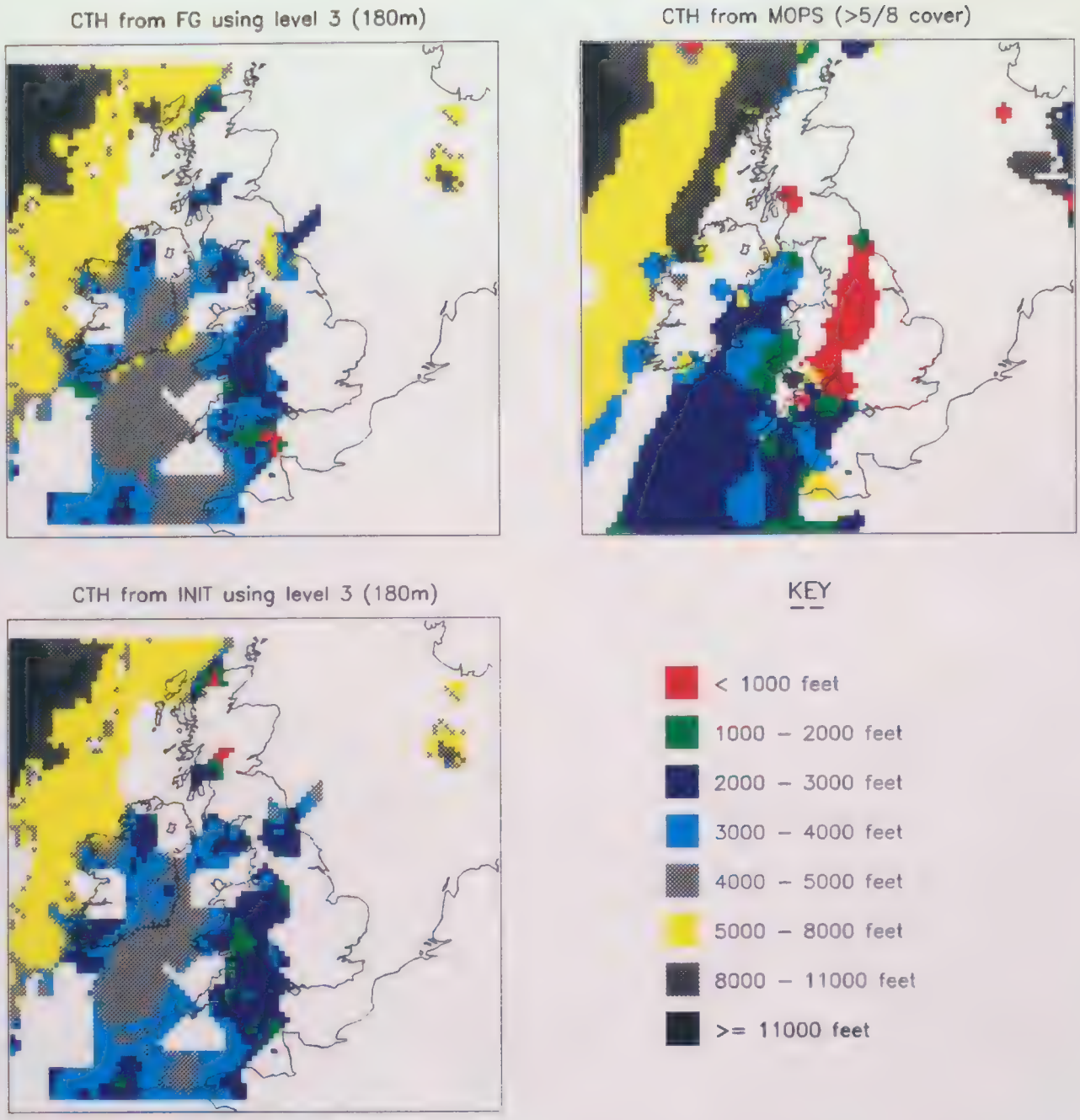

Figure 10.

Cloud top height (CTH) obtained from 3 sources each valid at 0000 GMT 30/12/92. The heights in the leftmost diagrams were derived using the test scheme from temperature and dewpoint data at model level three (approx 180m). In the upper picture a first guess (FG) 3 hour forecast was used to supply the temperature and dewpoint data. In the lower picture a T+0 (INIT) forecast start field was used. The height field in the diagram at the top right was derived from the results of the moisture observation pre-processing system (MOPS) which outputs cloud cover at model gridpoints. The height of the highest layer of cloud is shown provided that it covers more than 5/8 of a grid square. The CTHs in all diagrams are all relative to the model surface.

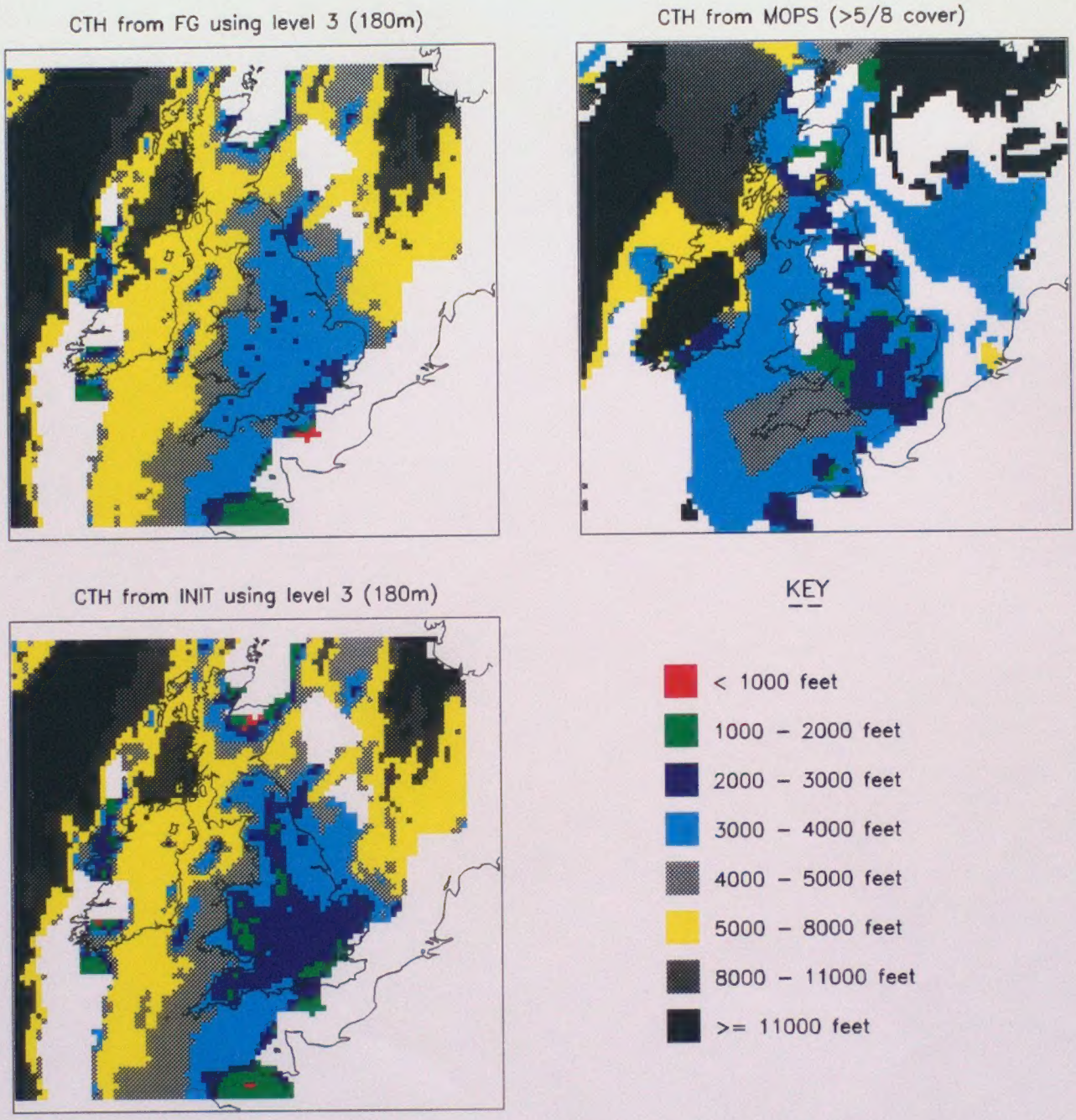

Figure 11.

Cloud top height (CTH) obtained from 3 sources each valid at 0600 GMT 08/03/93. The heights in the leftmost diagrams were derived using the test scheme from temperature and dewpoint data at model level three (approx 180m). In the upper picture a first guess (FG) 3 hour forecast was used to supply the temperature and dewpoint data. In the lower picture a T+0 (INIT) forecast start field was used. The height field in the diagram at the top right was derived from the results of the moisture observation pre-processing system (MOPS) which outputs cloud cover at model gridpoints. The height of the highest layer of cloud is shown provided that it covers more than 5/8 of a grid square. The CTHs in all diagrams are all relative to the model surface.

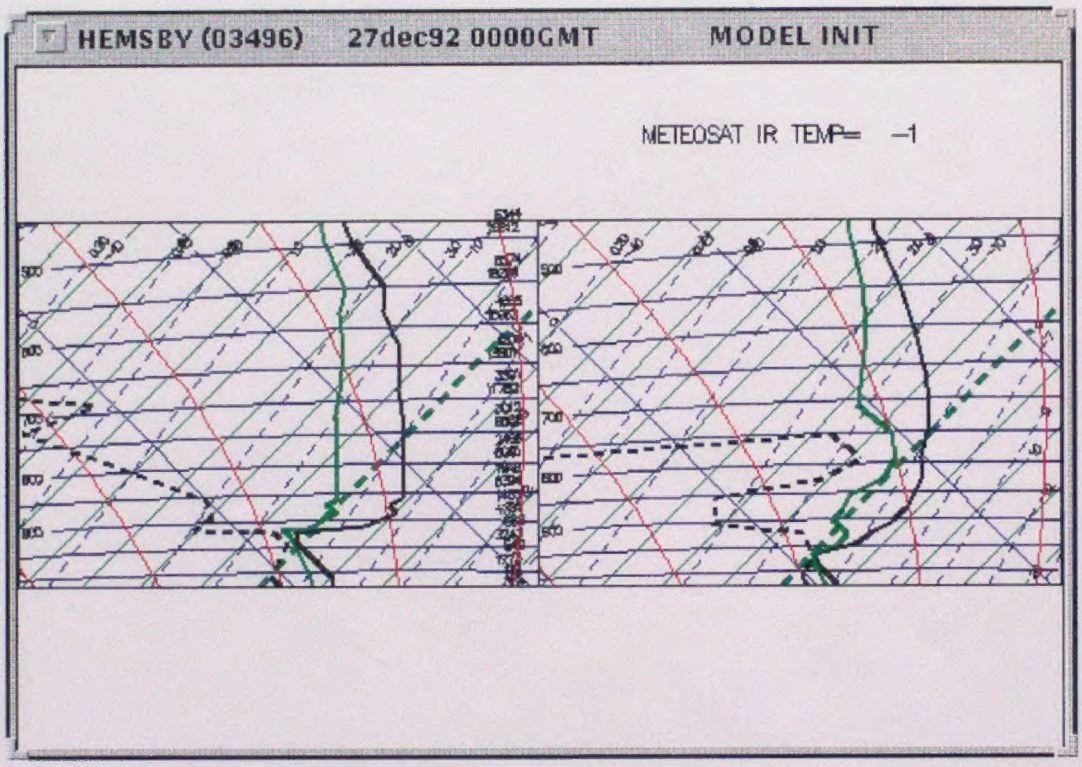

Figure 12.

Tephigrams for Hemsby (03496) for 27/12/92 at 0000 GMT. The sounding on the left is the observed, the plot on the right is from the NMM INIT for a nearby gridpoint. The METEOSAT IR temperature for this gridpoint is indicated above. Temperatures are shown as solid black lines, dewpoints as dashed lines and wet-bulb temperatures as solid green.

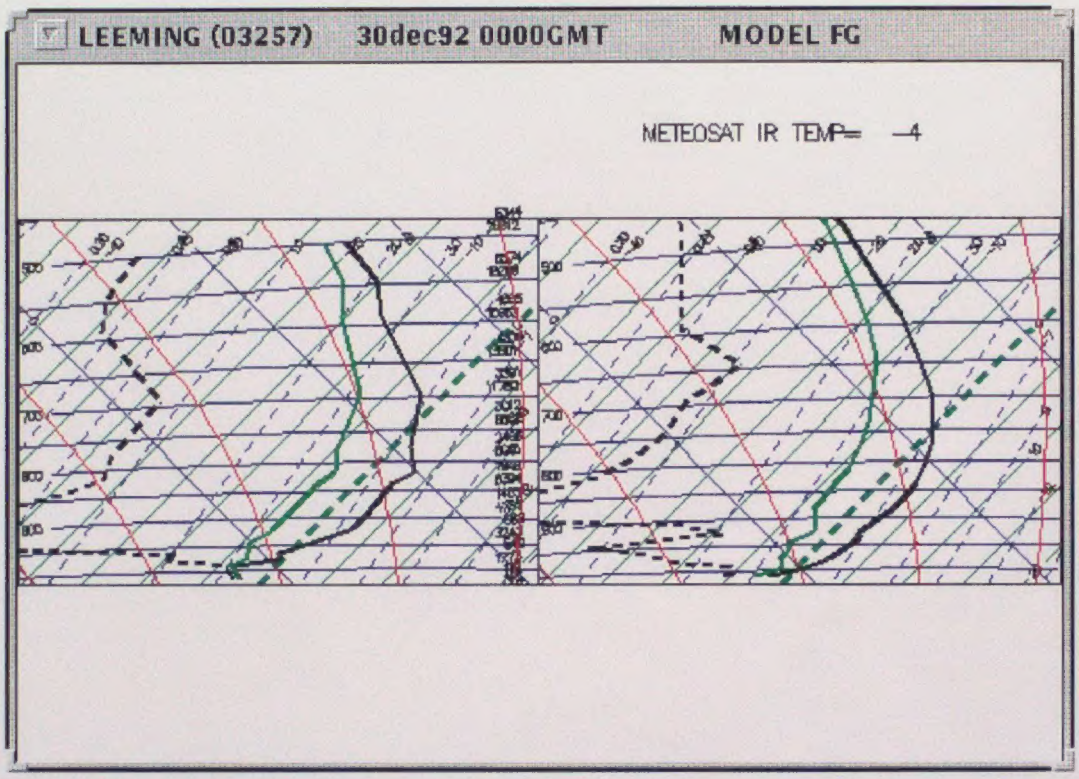

Figure 13.

Tephigrams for Leeming (03257) for 30/12/92 at 0000 GMT. The sounding on the left is the observed, the plot on the right is from the NMM FG for a nearby gridpoint. The METEOSAT IR temperature for this gridpoint is indicated above. Temperatures are shown as solid black lines, dewpoints as dashed lines and wet-bulb temperatures as solid green.

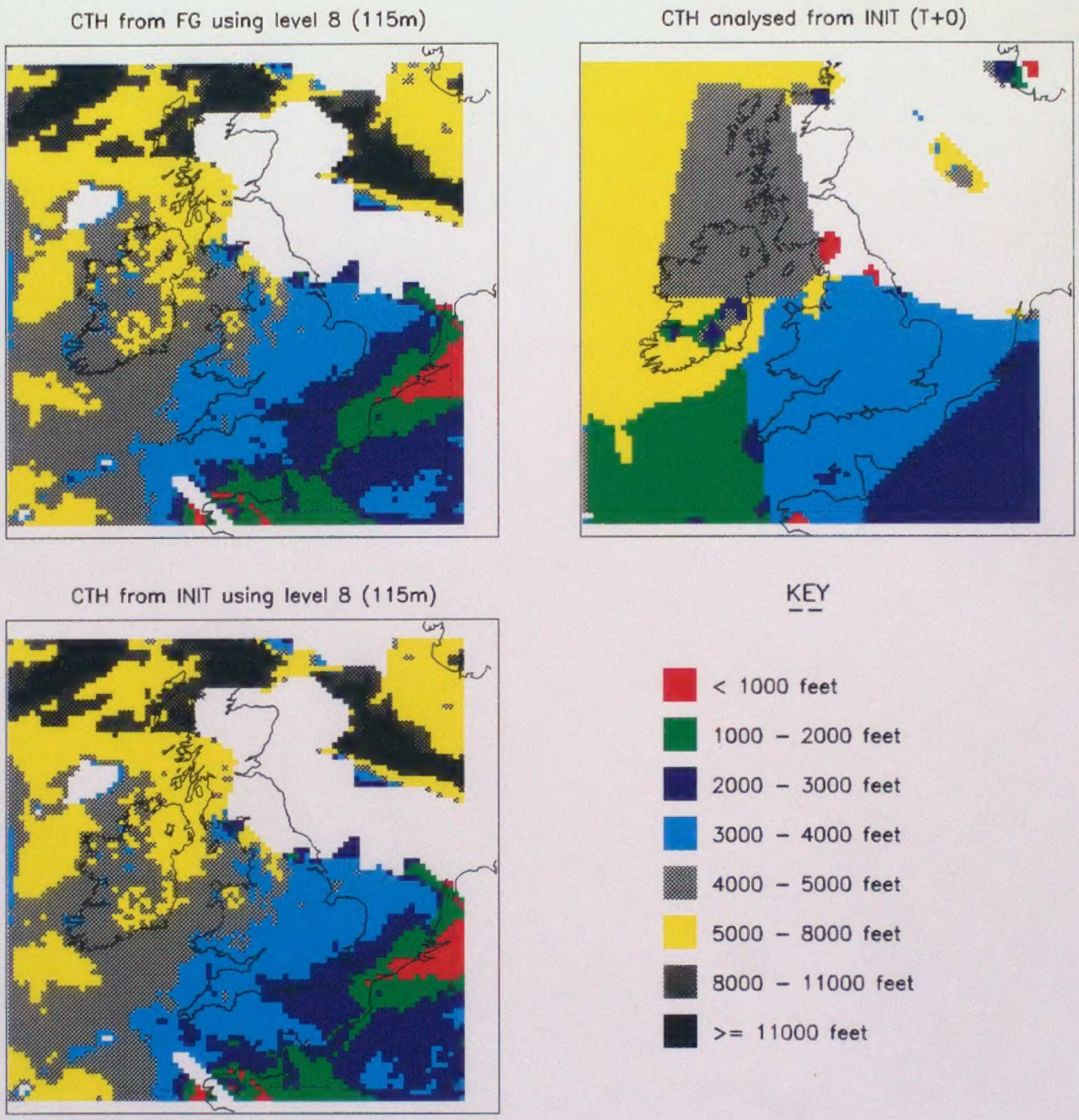

Figure 14.

Cloud top height (CTH) obtained from 3 sources each valid at 0000 GMT 04/12/91. The heights in the leftmost diagrams were derived using the test scheme from temperature and dewpoint data at model level eight (115m). In the upper picture a first guess (FG) 3 hour forecast was used to supply the temperature and dewpoint data. In the lower picture a T+0 (INIT) forecast start field was used.
The height field in the diagram at the top right was derived from the T+0 field and shows the height of the lowest layer of cloud where cloud cover is greater than 0.75. The CTHs in all diagrams are all relative to the model surface.